Does OH Trace the Diffuse (CO-Dark) Molecular Gas?

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``OH What a Lovely Molecule Workshop''

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Basic OH Chemistry in Diffuse Clouds

- Initial production of ions by cosmic rays
- Sequence of reactions leads to OH whether in diffuse atomic or diffuse molecular regions
- Some temperature sensitivity for key charge-exchange reaction

$$O^+ + H_2 \rightarrow OH^+ + H \qquad\qquad k = 10^{-9}\exp(-232/T_k)\ \mathrm{cm^3 s^{-1}}$$

- Molecular hydrogen required, but this is dominant form of hydrogen in ISM once visual extinction > few tenths mag. with standard ISRF
- OH destroyed primarily by photodissociation in low-extinction regions of the ISM

Simplified Schematic of OH Chemistry in Diffuse Clouds

$H + CR \rightarrow H^+ + e^-$ starting point in primarily-atomic regions

$H_2 + CR \rightarrow H_2^+ + e^-$ primarily, but also $\rightarrow H + H^+ + e^-$

$H^+ + O \rightarrow O^+ + H$ $k = 10^{-9}\exp(-232/T_k)$ [sets temperature dependence of OH abundance]

$O^+ + H_2 \rightarrow OH^+ + H$ depends on H2 abundance

$OH^+ + H_2 \rightarrow H_2O^+ + H$

$OH^+ + e \rightarrow O + H$

$H_2O^+ + e \rightarrow OH + H_2$ importance depends on fractional ionization

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$ $k = 10^{-3} * k_{dissoc\ recomb}$ so dominates if $X(e) < 10^{-4}$ (only C^+ providing e)

$H_3O^+ + e \rightarrow OH + H + H$ (also $\rightarrow OH + H_2$; $H_3O^+ + H_2$ is endothermic)

$OH + h\nu \rightarrow O + H$ continuum photodestruction; rate ~$3.9 \times 10^{-10}\exp(-A_v)$

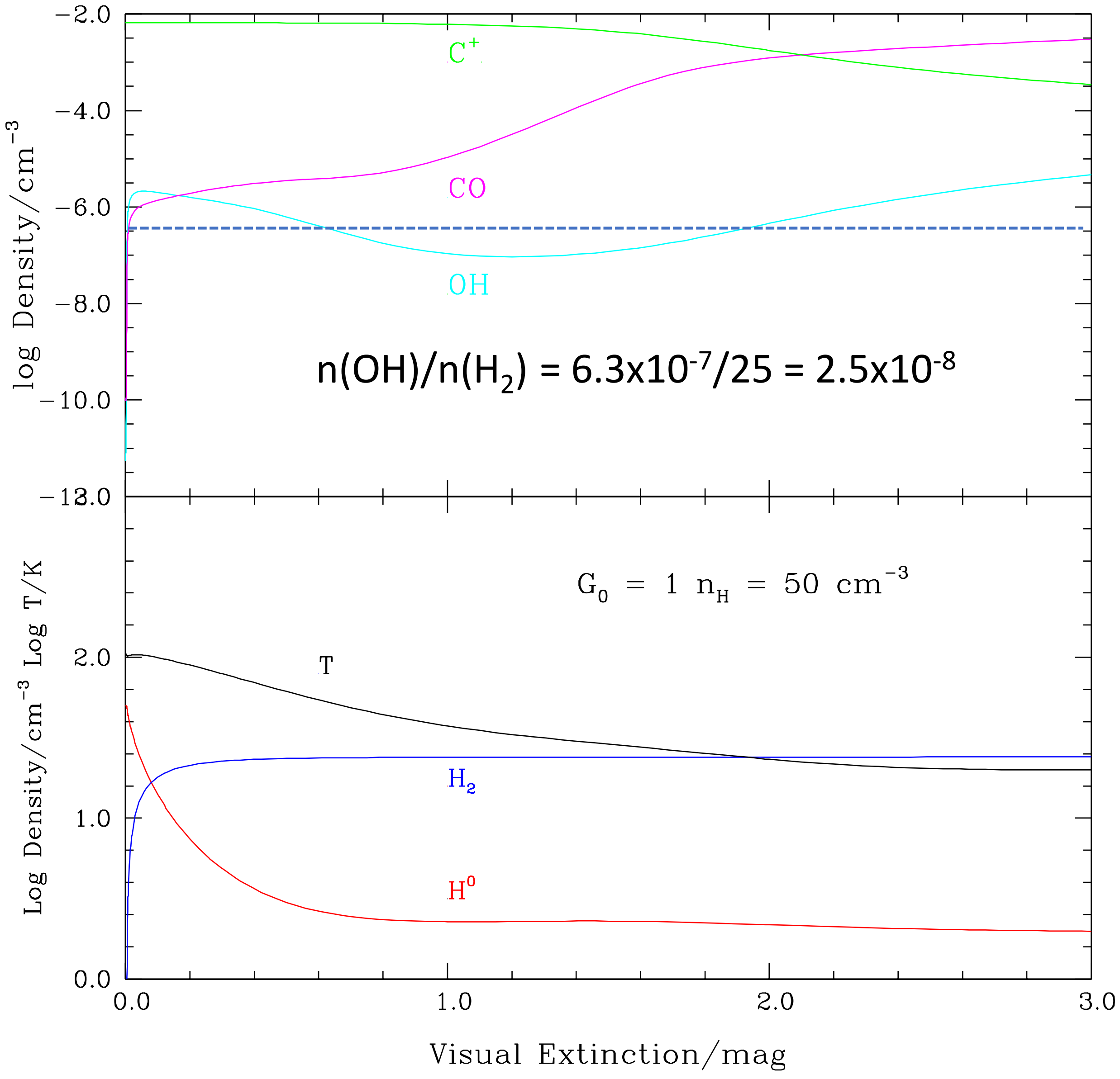
$OH + O \rightarrow O_2 + H$ [not so important for OH but critical for making O_2]

OH also destroyed by reactions with He^+, C^+, C, ….

Glassgold & Langer (1976); UMIST Database

Meudon PDR Code Employed to Evaluate OH Abundance Under Different Conditions

- All runs have total extinction equal to 10 mag
- ISRF is standard (G_0 = 1) or 10x standard (G_0 = 10)
- Hydrogen nucleus density, n_H, is 50 cm^{-3} or 100 cm^{-3}
- Standard cosmic ray rates throughout; no enhanced rate at cloud edges as indicated by e.g. H_3^+ and other chemical tracers
- Standard grain properties
- Depleted sulfur abundance in accordance with most modeling



Key Aspects of Code Output

For standard ISRF, H-H_2 transition occurs at A_v ~ 0.1 mag: hydrogen is largely atomic throughout

TK ~ 25 K for A_v > 1 mag (a little low) but rises to 200 K at cloud edge

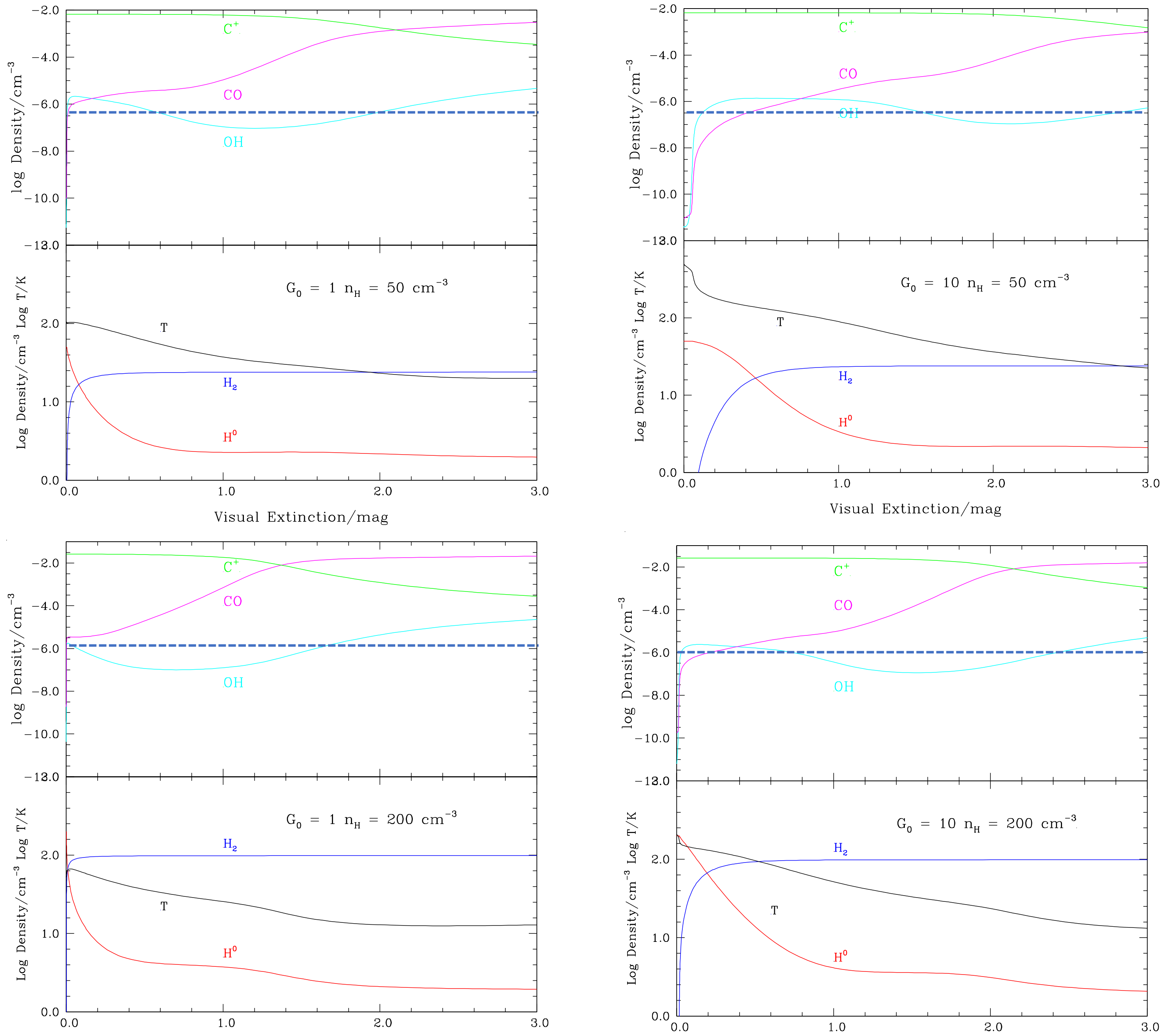
Chemistry:

C^+ is dominant form of carbon for $A_v < 2$ mag

X(CO) = 1.6×10^{-4} in interior of cloud but drops precipitously to ~8×10^{-8} for $A_v < 1$ mag

OH abundance relatively constant at 1.2×10^{-8} THROUGHOUT 0.05 mag < A_v < 3 mag

OH is a more unbiased tracer than CO of regions with $A_v < 3$ mag



OH is remarkably resilient tracer of total hydrogen nucleus density throughout the range $0 < A_V < 3$ mag., according to chemical modeling

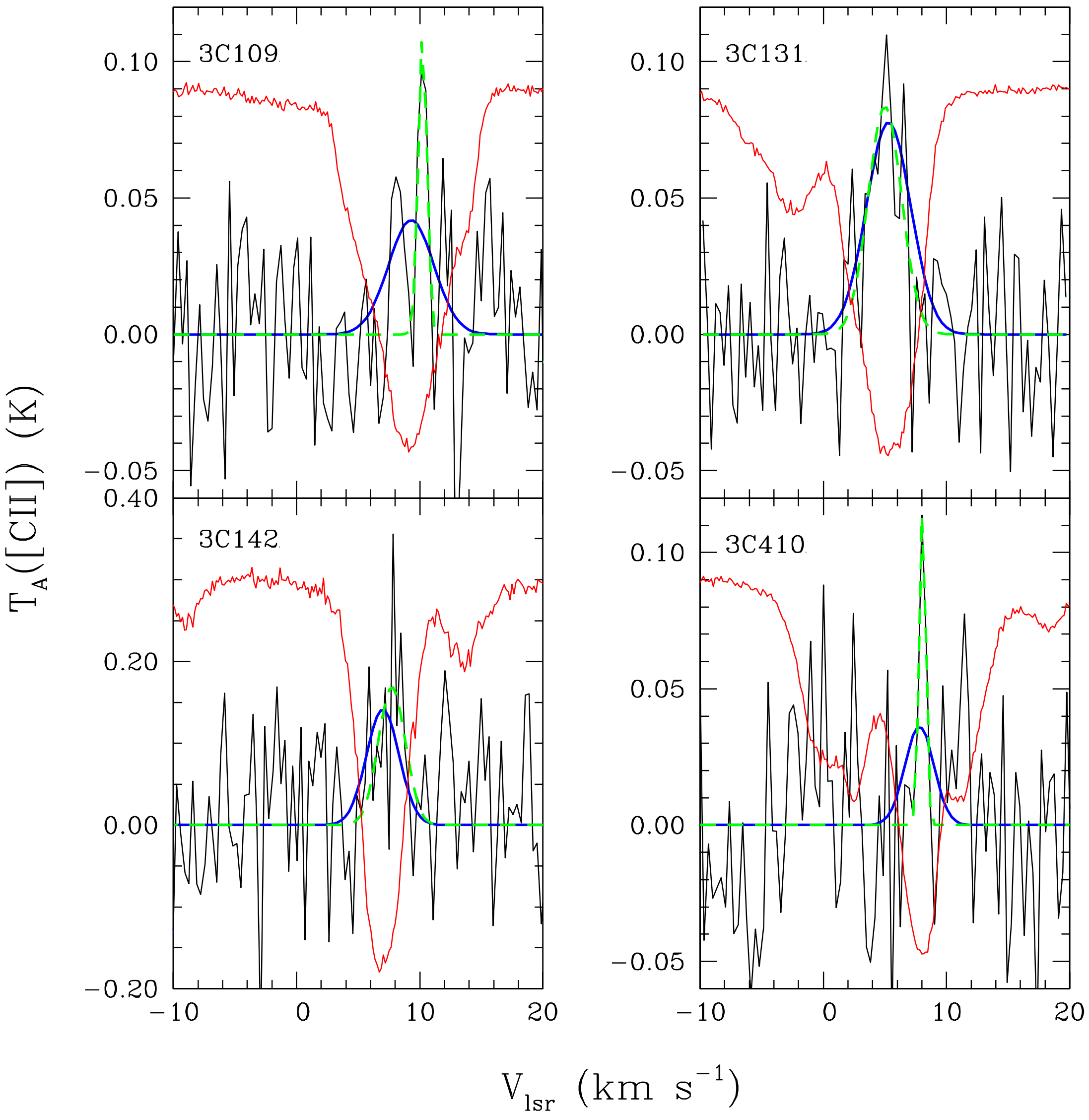
Higher temperature at cloud edge for higher G0 increases formation rate but also the photodestruction rate

No substantial variation – unlike CO which depends on self-shielding for protection against line photodissociation, and C^+ which disappears when CO builds up.

Higher density pushes H^0/H_2 transition to lower A_V, compensating the effect of higher G_0.

Four Diffuse Molecular Clouds Studied in [CII] Emission (SOFIA upGREAT) by Goldsmith et al. ApJ, 2018

- Lines of sight towards quasars providing background for cm spectral line observations
- H^0 column density from 21cm (AO Millenium Study; Heiles & Troland 2003)
- Total hydrogen nucleus column density $N(H^0)+2N(H_2)$ from visual extinction (Planck; Ade et al. 2016)
- Assuming carbon fractional abundance and with kinetic temperature known from 21cm absorption/emission data, the observed [CII] emission can be converted to volume density and thermal pressure



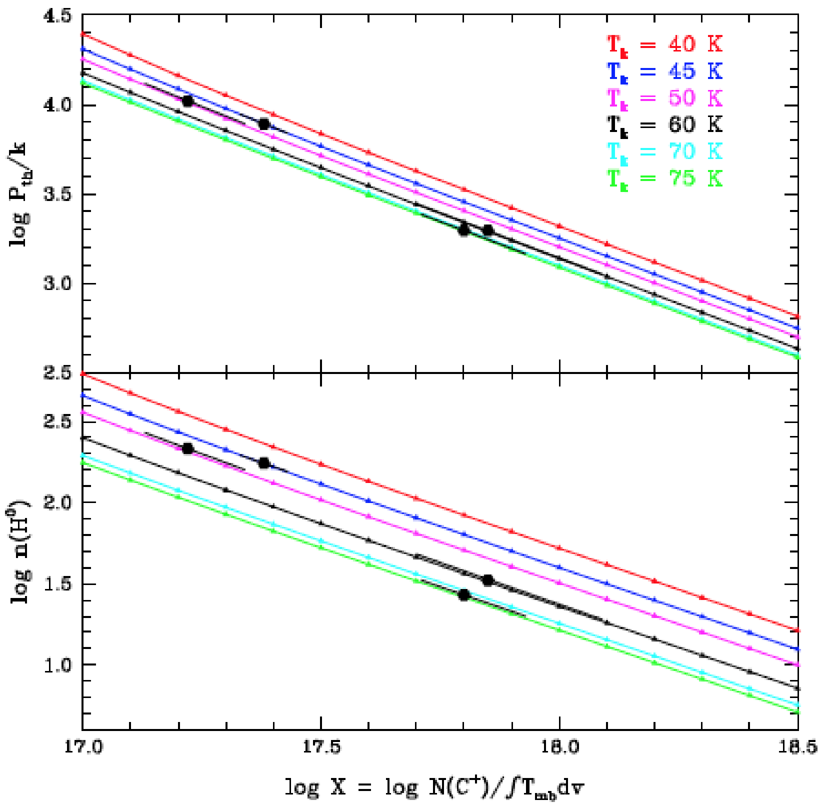
Black = [CII] 158µm; Blue = Gaussian fit; Red = 21 cm absorption 0 ≤ $(1\text{-}e^{-\tau})$ ≤ 1.1

- [CII] is weak; average 14 pixels of upGREAT array to get detections in 3+ of four sources
- The [CII] emission agrees well with strongest component of HI CNM absorption

$$n(\mathrm{H}^0) = 4.6 \times 10^{18}(100/T_k)^{0.14}e^{91.21/T_k}X^{-1}.$$

$$X = \frac{N(\mathrm{C}^+)}{\int T_{\mathrm{mb}}dv}\ \mathrm{cm}^{-2}(\mathrm{K\ km\ s}^{-1})^{-1},$$

Source	$N(H^0)$			N_H[b]	A_v[c] (mag)	$2N(H_2)$	$f(v([C\ II])$[d] CNM	$2N(H_2)$ $v([C\ II])$	Molecular Fraction $f(H_2)$
	CNM + WNM[e]	CNM[f]	CNM $v([C\ II])$[g]						
1	2	3	4	5	6	7	8	9	10
3C109	20.8	15.5	11.5[h]	35.2	1.88	14.4	0.74	10.6	0.48
3C131	28.6	11.3	7.1[i]	51.5	2.75	22.9	0.63	14.4	0.67
3C142	22.0	8.1	7.1[j]	22.8	1.22	0.9	0.87	0.8	0.10
3C410	48.2	15.4	7.1[k]	78.8	4.21	30.6	0.46	14.1	0.66

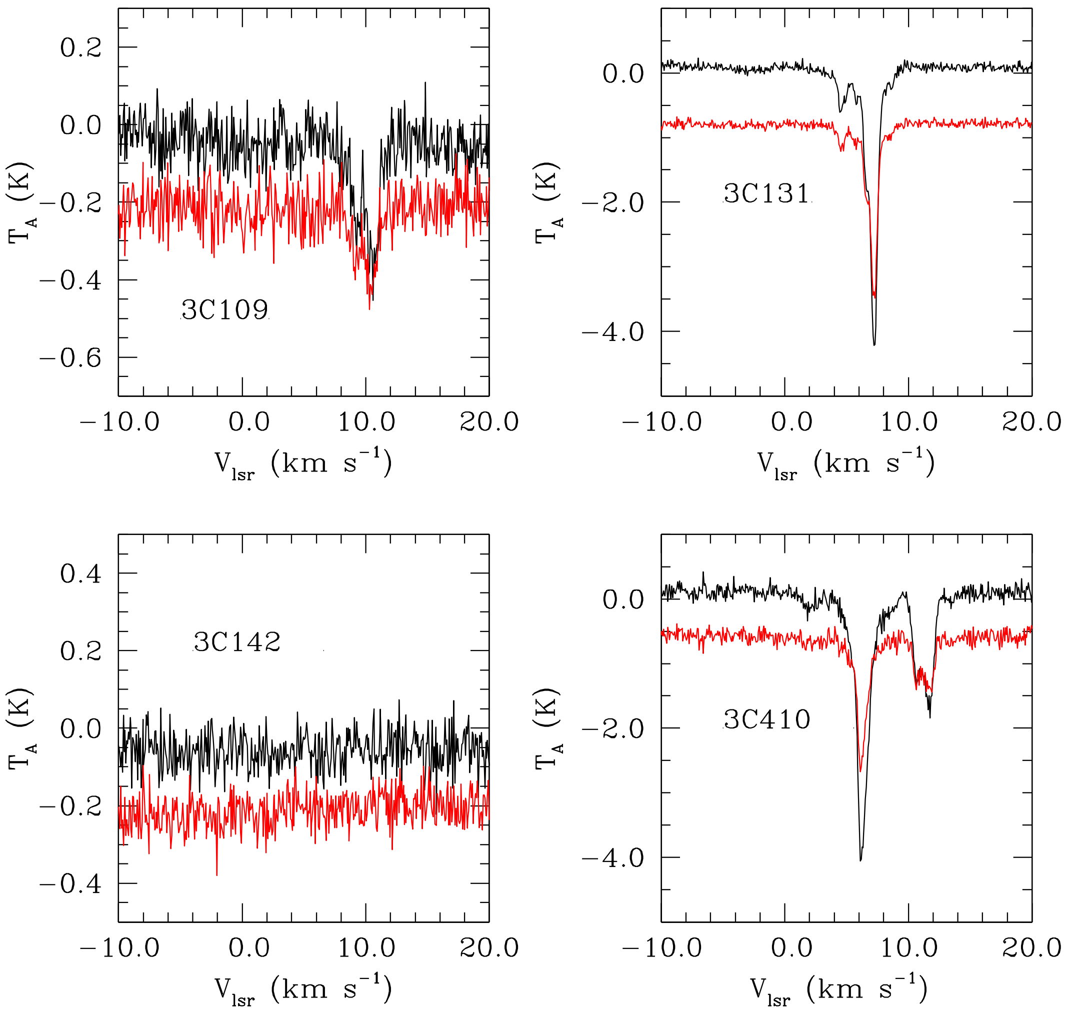


Source	T_k[a] (K)	$\int T_{mb} dv$ (K km s^{-1})	H^0 only				H^0 and H_2			
			$N(C^+)$[b]	X[c,d] ([i])	n[d,e] (cm^{-3})	P_{th}/k[d,f] (cm^{-3} K)	$N(C^+)$[g]	X ([i])	n[h] (cm^{-3})	P_{th}/k (cm^{-3} K)
1	2	3	4	5	6	7	8	9	10	11
3C109	73	0.290 ± 0.072	1.9	$6.4_{5.1}^{8.5}$	27_{20}^{33}	1970_{1450}^{2430}	3.6	12_{10}^{16}	15_{11}^{19}	1110_{840}^{1400}
3C131	45	0.476 ± 0.055	1.1	$2.4_{2.2}^{2.7}$	170_{150}^{200}	7790_{6900}^{8810}	3.5	$7.3_{6.5}^{8.2}$	63_{55}^{71}	2860_{2480}^{3210}
3C142	49	0.681 ± 0.162	1.1	$1.7_{1.4}^{2.2}$	210_{160}^{270}	10440_{7770}^{13090}	1.3	$1.8_{1.5}^{2.4}$	190_{150}^{250}	9360_{7150}^{12000}
3C410	59	0.160 ± 0.066	1.1	$7.2_{5.1}^{12.2}$	33_{19}^{47}	1970_{1130}^{2790}	3.4	21_{15}^{36}	13_{8}^{18}	750_{440}^{1070}

- Clouds show a wide variety of density and thermal pressure
- Overall, results are reasonably consistent with expectation for diffuse molecular clouds and ISM physics
- Details depend on assumptions about mixing of H^0 and H_2

OH Also Observed in the AO Millenium Survey

Thanks to C. Heiles for providing data



- Absorption is very sensitive compared to emission since T_A proportional to T_{BG} rather than Tex, and Tex is only a few K while T_{BG} can be ~100 K with Arecibo
- High signal to noise ratio allows disentangling multiple velocity features along LOS
- OH features detected in 3 of 4 sources
- Velocities and widths generally agree with [CII] but some interesting differences relative to HI
- Calculate OH column density:
  - Assume optically thin
  - Ignore population of levels above J = 3/2. This is reasonable given ~120 K energy above ground state, and n_{crit} ~ few thousand cm^{-3}, which is >> volume density of these clouds.
  - Electron excitation may be significant
- $N(OH) = 2.25\times10^{14}\ T_{ex} \int \tau dv$
  - The excitation temperature introduces significant uncertainty but this is minimized if we know the density and can do a statistical equilibrium calculation.

OH collisional Excitation

- This is a matter of surprising complexity. New quantum calculations by Klos et al. (2017, MNRAS, 471, 4249) treat collisions with H_2, which is dominant collision partner.
- Rate coefficients are mostly larger by factor 2-3 than those previously used (with some exceptions) resulting in smaller OH column densities
- See Klos, Lique, & Alexander (2007, Chem. Phys. Letters, 445, 12) for collisions with H^0 (actually He)
- The excitation temperature does depend on cloud density, but has lower bound of 2.7 K, and generally does not exceed 10 K (using densities determined in 4 clouds studied.
- Adopt excitation temperature of 5 K now; this produces +/- factor of 2 uncertainty in N(OH) which could be reduced by more careful modeling

Correlations Between N(OH) and $N_H = N(H^0) + 2N(H_2)$

Adopt T_{ex} = 5 K for all sources

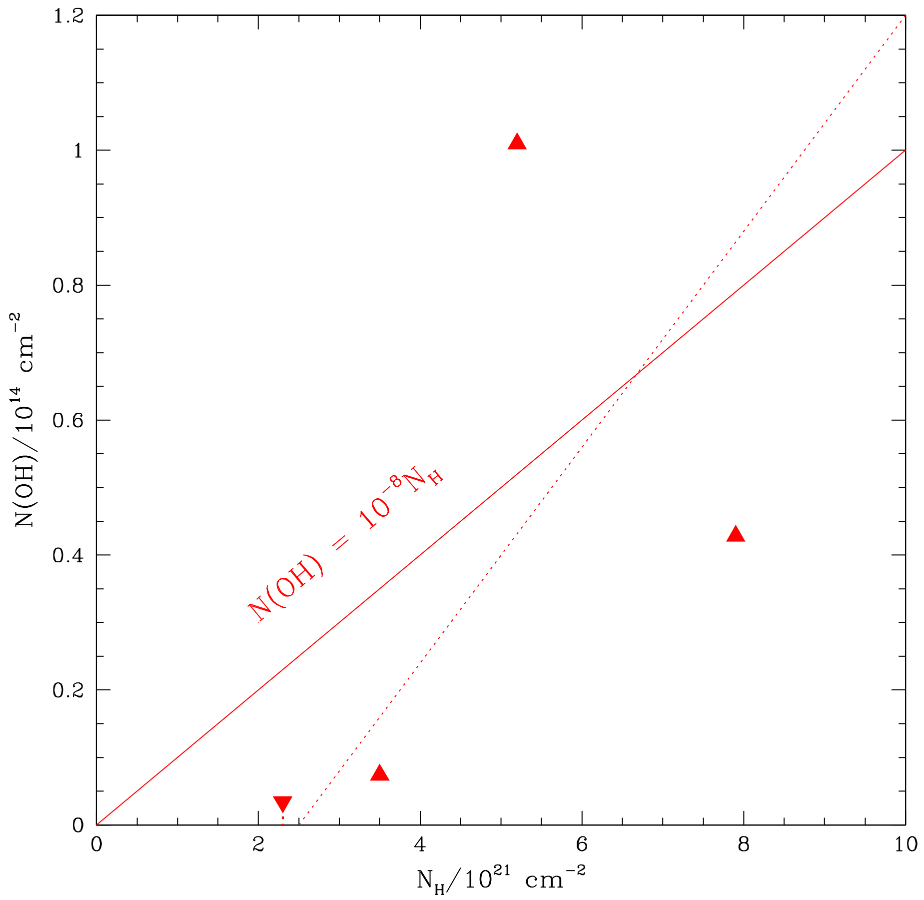
- Solid red line is eyeball fit that goes through origin

  $N(OH) = 10^{-8} N_H$

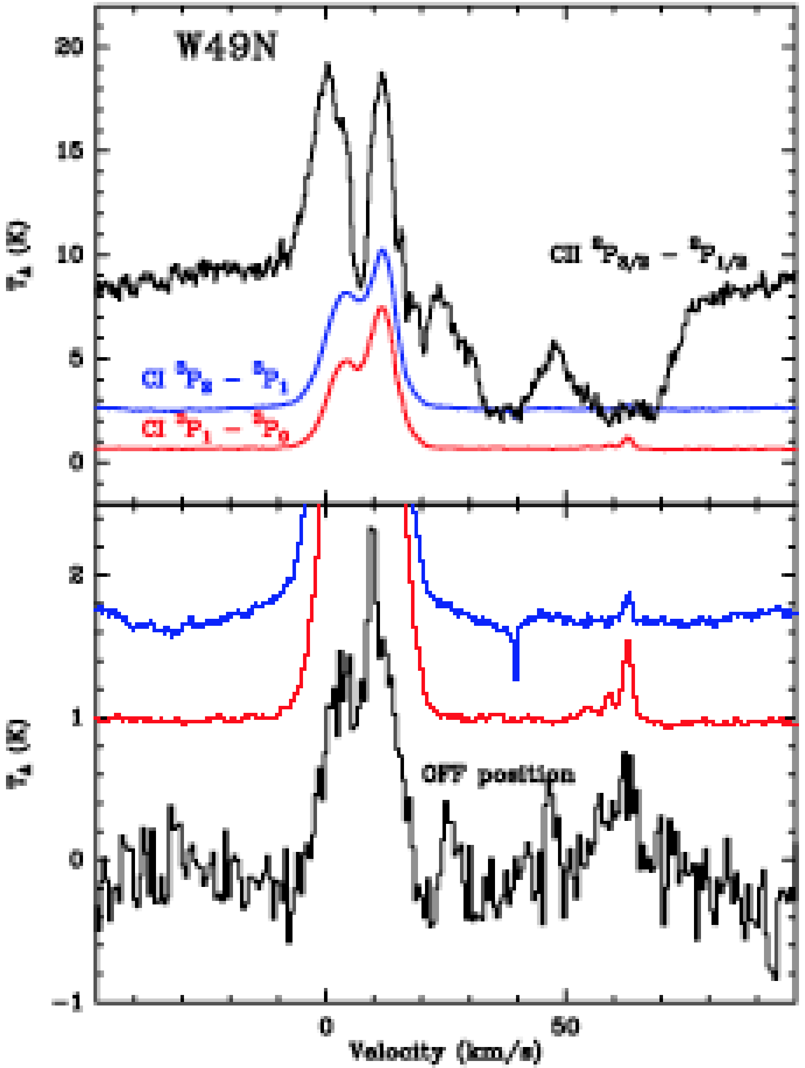
- Suggestion that there is a threshold for OH at present level of sensitivity at $N_H \sim 2.5 \times 10^{21}$ cm^{-2} (A_v =~1.2 mag)
- Dashed red line is eyeball it not so constrained

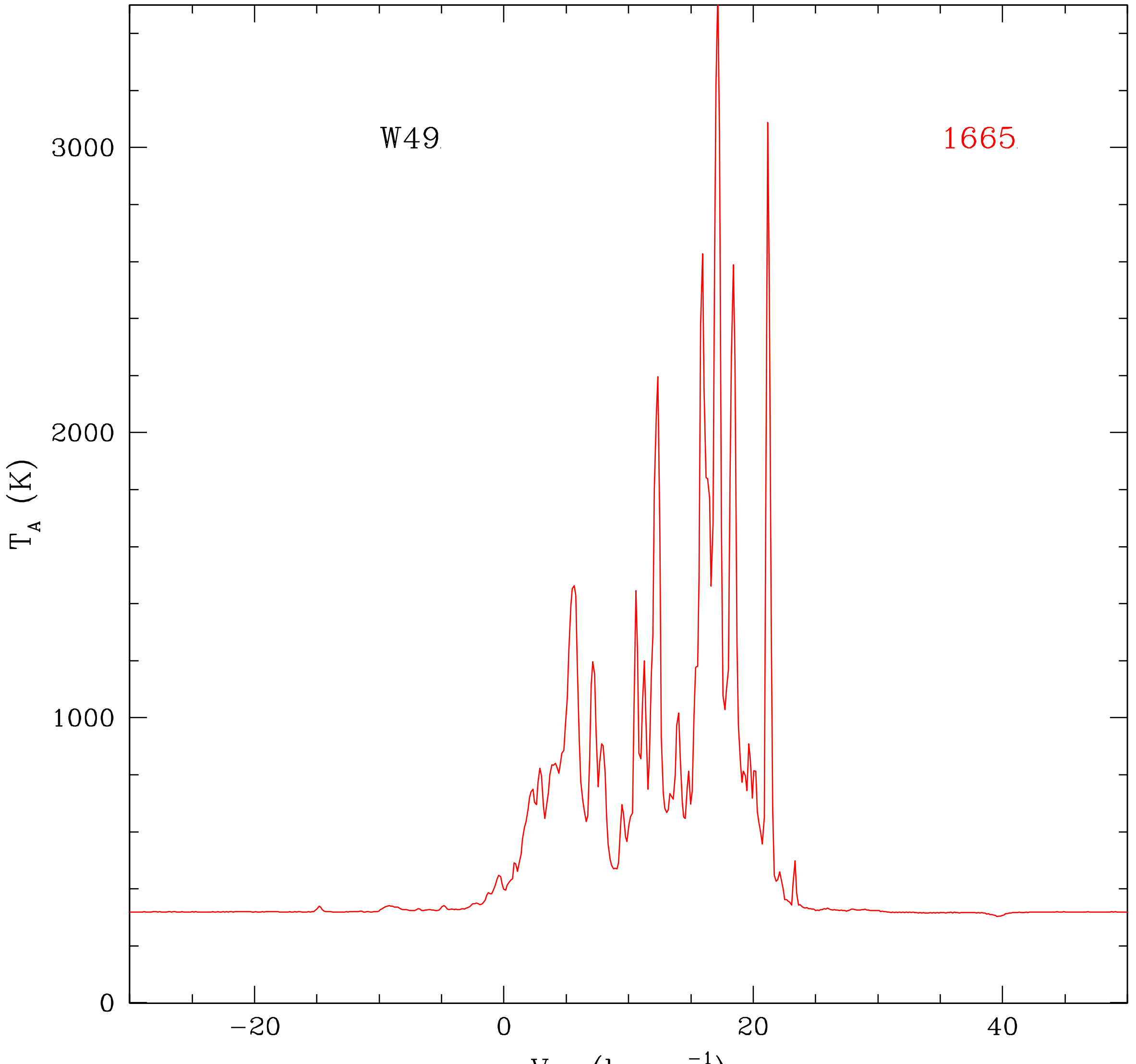
  $N(OH) = 1.6 \times 10^{-8} [N_H - 2.5 \times 10^{21}\ cm^{-2}]$

THIS IS IN GOOD AGREEMENT WITH THE PREDICTION OF THE MEUDON CHEMICAL MODEL

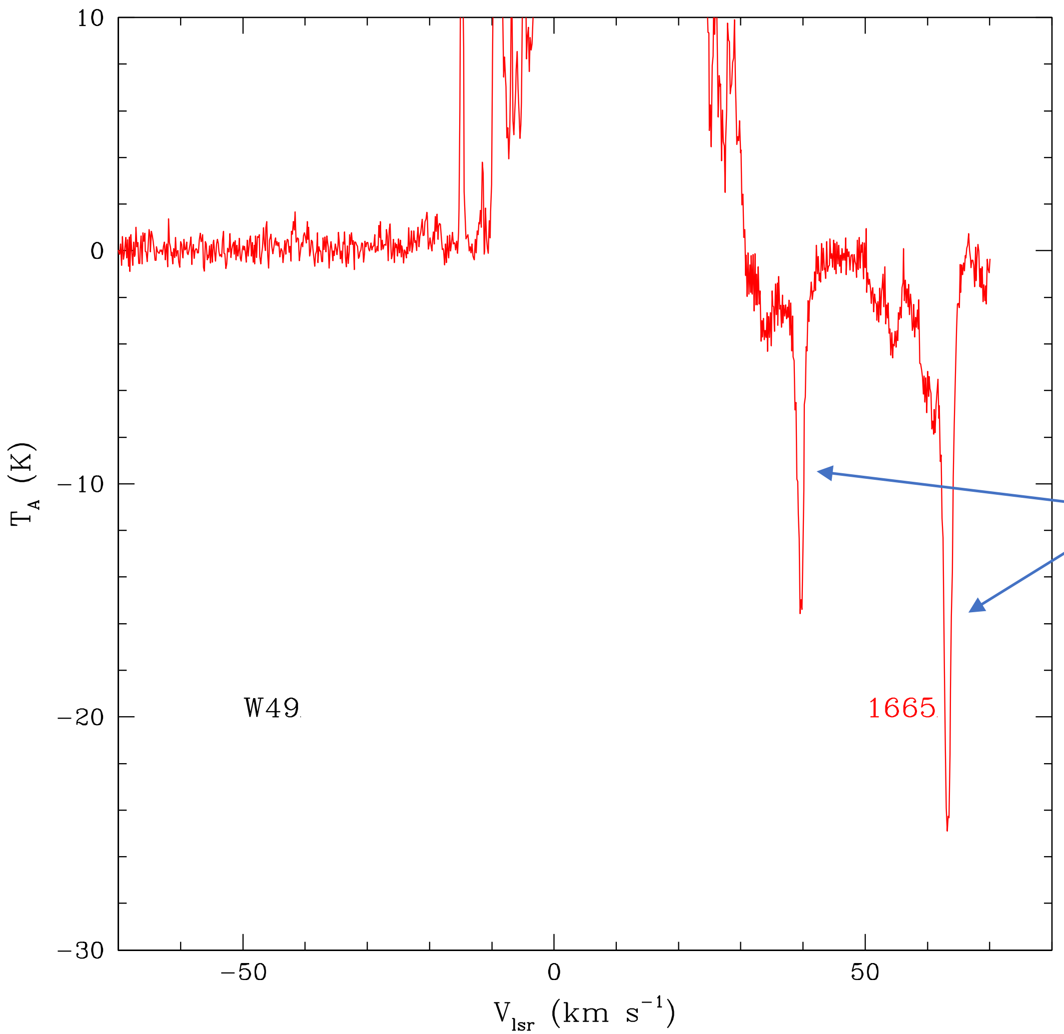


W49: Massive GMC/Star-forming Region and Strong IR/Submm Continuum Source – BUT AN OH MASER!





Even for W49 Information on Absorption features seen in [CII] is Available



Useful for comparison with e.g [CII] and H^0

Conclusions

- OH chemistry in diffuse clouds seems reasonably well understood
- With reasonable radiation field and density, hydrogen is molecular throughout the "diffuse molecular cloud"
- Predicted OH fractional abundance X(OH) = n(OH)/n(H_2) = $1\text{-}2 \times 10^{-8}$
- Lines of sight to four extragalactic continuum sources, allowing examination of entire column through Milky Way
- Observed in [CII] emission, dust emission, 21 cm and OH absorption
- Modeling allows determination of density, H_2 fraction, total hydrogen column density and other parameters
- The OH fractional abundance ~2×10^{-8} in these sources, consistent with chemical model and confirming that **OH IS A GOOD TRACER OF CO-DARK MOLECULAR GAS**